

# Mass transfer dynamics in double degenerate binary systems

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**Abstract.** We present a numerical study of the mass transfer dynamics prior to the gravitational wave-driven merger of a double white dwarf system. Recently, there has been some discussion about the dynamics of these last stages, different methods seemed to provide qualitatively different results. While earlier SPH simulations indicated a very quick disruption of the binary on roughly the orbital time scale, more recent grid-based calculations find long-lived mass transfer for many orbital periods. Here we demonstrate how sensitive the dynamics of this last stage is to the exact initial conditions. We show that, after a careful preparation of the initial conditions, the reportedly short-lived systems undergo mass transfer for many dozens of orbits. The reported numbers of orbits are resolution-biased and therefore represent only lower limits to what is realized in nature. Nevertheless, the study shows convincingly the convergence of different methods to very similar results.

## 1. Introduction

White dwarfs that merge under the influence of gravitational waves have been suspected to be related to a variety of phenomena. Although not being the most popular model for type Ia supernovae, white dwarf mergers have despite several ups and downs defended their position as a serious, possible progenitor model (Iben & Tutukov 1984, Webbink 1984, Yoon et al. 2007). If ignited at the surface, merger remnants have been found to be transformed into an O-Ne-Mg white dwarf that finally forms a neutron star in an accretion-induced collapse (Saio & Nomoto 1985, Nomoto & Kondo 1991, Saio & Nomoto 2004). Merged low-mass white dwarf mergers are thought to produce extreme helium stars and the majority of R Corona Borealis stars, e.g. Saio & Jeffery (2002). A fraction of white dwarf binaries may evolve into systems that survive the onset of mass transfer and evolve to longer periods with ever decreasing mass transfer rate (e.g. Paczyński 1967, Nelemans et al. 2001), so-called AM CVn systems.

The merger process of two white dwarfs has been modeled by a number of groups, Benz et al. (1990), Rasio & Shapiro (1995), Segretain et al. (1997), Guerrero et al. (2004), Yoon et al. (2007), all of the mentioned approaches used the SPH method. Recently, grid-based simulations (D’Souza et al. 2006, Motl et al. 2007) were performed where the authors carefully tried to reduce the angular momentum non-conservation due to advection errors that often plagues grid-based codes, see e.g. New & Tohline (1997). Their results are very different from most previous SPH simulations in the sense that their donor stars are not destroyed on a dynamical time scale, but instead show long-lived mass transfer over many orbital periods. These results have sparked some discussion about the stability of mass transfer in double degenerate systems during these stages, see e.g. Fryer & Diehl (2008).

In the following, we will demonstrate the sensitivity of the simulation dynamics on the exact

initial conditions and show that with accurately constructed starting configurations long-lived mass transfer ensues.

## 2. Model

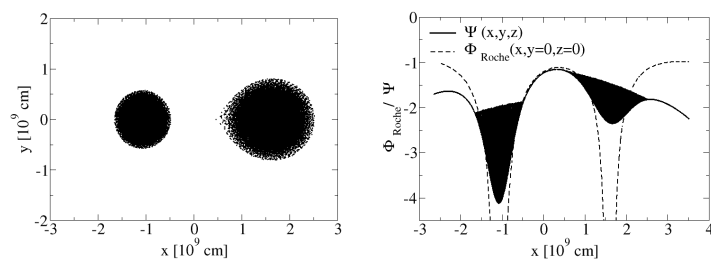
### 2.1. Numerical model

We use the smoothed particle hydrodynamics method to solve the 3D equations of fluid dynamics. Our code is documented in Rosswog et al. (2008). The system of fluid equations is closed by the HELMHOLTZ equation of state (Timmes & Swesty 2000). It accepts an externally calculated nuclear composition and allows a convenient coupling to a nuclear reaction network. We use a minimal nuclear reaction network (Hix et al. 1998) to determine the evolution of the nuclear composition and to include the energetic feedback onto the gas from the nuclear reactions. A set of only seven abundance groups greatly reduces the computational burden, but still reproduces the energy generation of all burning stages from He burning to NSE accurately. We use a binary tree (Benz et al. 1990) to search for the neighbor particles and to calculate the gravitational forces.

### 2.2. Initial conditions

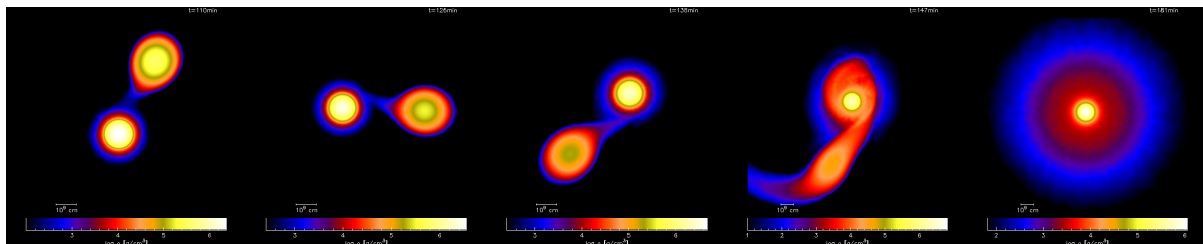
The dynamics of the binary systems is very sensitive to the initial conditions, therefore, it is vital to start the simulations from a setup that is as accurate as possible. Most of the previous SPH simulations (e.g. Benz et al. 1990, Segretain et al. 1997, Guerrero et al. 2004, Yoon et al. 2007) started from rather approximate initial conditions and consequently found a very large initial mass transfer rate and a subsequent disruption of the donor star within a few orbits.

In this work, we restrict ourselves to corotating initial configurations, but very carefully construct initial conditions along the strategy outlined by Rosswog et al. (2004). In a first step the (isolated) stars are “relaxed” individually into hydrostatic equilibrium by adding a velocity-proportional damping term to the momentum equation. Subsequently, we place the stars in the corotating frame at a separation  $a$ , that is large enough to avoid immediate mass transfer. This separation is then adiabatically reduced according to  $\dot{a} = -\frac{a}{\eta \cdot \tau_{\text{dyn}}}$ , so that  $\frac{a}{\dot{a}} \gg \tau_{\text{dyn}}$ . Here,  $\tau_{\text{dyn}}$  is the larger of the two white dwarf dynamical time scales and  $\eta$  takes values between 10 and 30. Once the first SPH particle crosses the  $L_1$  point of the Roche potential, the binary is set on a circular orbit. This moment was adopted as the time origin of the simulation. An example of a corotating equilibrium configuration at this stage (masses of  $0.6 M_\odot$  and  $0.9 M_\odot$ ) is shown in Fig. 1, left panel. The right panel shows a comparison between (point mass) Roche potential and the corresponding values as calculated from the real matter distribution.



**Figure 1.** Equilibrium configuration ( $0.9$  and  $0.6 M_\odot$ ) at onset of mass transfer. *Left:* projection of SPH particles onto the orbital plane, *right:* projection onto the  $(x, \Phi_{\text{Roche}}/\Psi)$  plane. The dashed line is the Roche potential as calculated for a point mass binary,  $\Phi_{\text{Roche}}(x, y = 0, z = 0)$ . The solid black line is the corresponding quantity as derived from the real mass distribution,  $\Psi(x, y = 0, z = 0)$ , and is given by  $\Psi(\mathbf{r}) = \phi(\mathbf{r}) - \frac{1}{2}(\boldsymbol{\omega} \times \mathbf{r})^2$ , where  $\phi(\mathbf{r})$  is the gravitational potential.

### 3. From the onset of mass transfer to a possible disruption



**Figure 2.** Dynamical evolution of a double white dwarf system with  $q = 0.5$  (at 44, 50, 56, 59 and 67 times the initial binary period.)

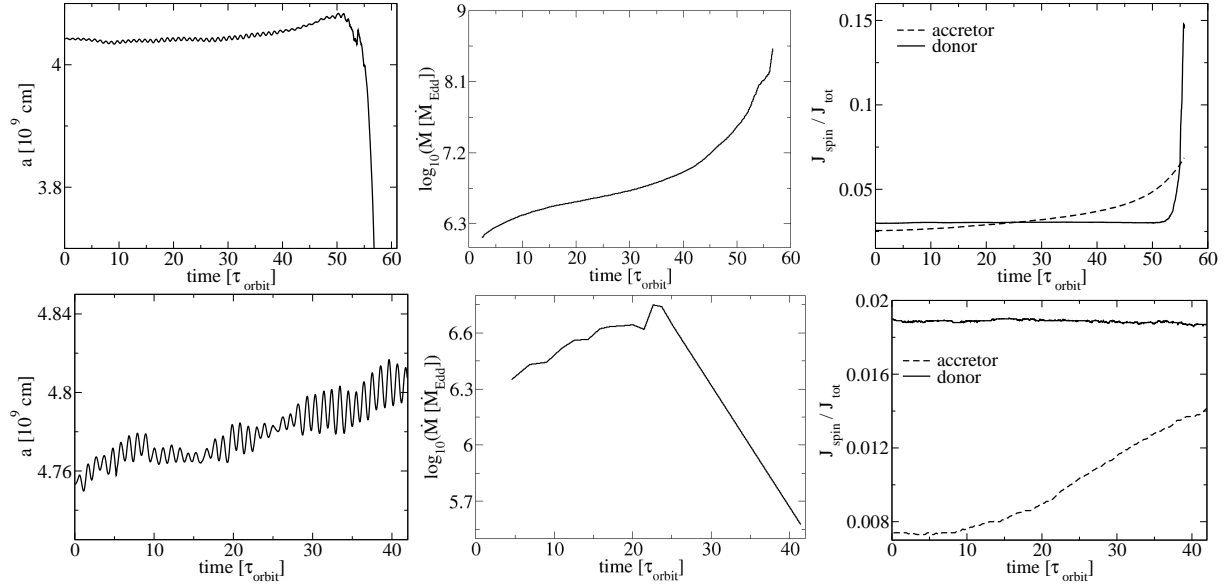
Exemplary for a large set of simulations that will be presented elsewhere (Dan et al. 2009) we show the evolution of two binary systems: one with  $q = M_{\text{donor}}/M_{\text{accretor}} = 0.5$  to be compared to Rasio & Shapiro (1995), D’Souza et al. (2006), and another one with  $q = 0.27$ . Rasio & Shapiro (1995) also used an SPH approach while D’Souza et al. (2006) used a grid-based code. Although we think that our investigated systems are close enough to Rasio & Shapiro (1995), D’Souza et al. (2006) to warrant a fair comparison, one has to keep in mind that the latter investigations use 5/3-polytropes while we use a physical EOS. Since the EOS governs, via the mass-radius relationship, how the star reacts on mass loss, it also influences the orbital evolution. Thus, the comparison should be taken with a grain of salt.

We carry out the simulation of the  $q = 0.5$  case ( $0.3$  and  $0.6 M_{\odot}$ ) at two different resolutions. First, we use  $\approx 4 \times 10^4$  SPH particles to conform the simulations of Rasio & Shapiro (1995). We find an initial separation where (numerically resolvable) mass transfer sets in that is larger by 27 percent than in Rasio & Shapiro (1995). While in Rasio & Shapiro (1995) the binary was disrupted within five orbits, we count more than 18 full orbits before the disruption sets in.

In a second simulation of the same system we use  $2 \times 10^5$  SPH particles, see Fig. 2, and consequently the initial separation increases slightly since we are now better resolving the outer stellar layers. The main purpose of this run is the comparison with D’Souza et al. (2006) who, in turn, ran their calculation to compare against Rasio & Shapiro (1995). D’Souza et al. (2006) found the orbital separation to be constant for about 20 orbits, then it increased and the mass transfer rate leveled off without any sign of a merger. After 32 orbits the simulation was stopped. We followed our simulation for an even longer time. Similar to D’Souza et al. (2006) the orbital separation increases slightly but in the end the donor is still disrupted, although only after as many as 60 orbital revolutions, see panel 4 in Fig. 2. Thus, for as long as we can compare, our simulations are in perfect agreement with D’Souza et al. (2006). We also explore the evolution of a binary with a mass ratio of  $q = 0.27$  ( $0.3$  and  $1.1 M_{\odot}$ ). Contrary to our previous example where we saw a direct impact onto the accretor, see Fig. 2, panel 1, now the circularization radius is larger than the accretor radius and a disk forms. This configuration feeds back angular momentum into the orbit thereby increasing the orbital separation, Fig. 3, bottom left. This de-circularizes the orbits from the beginning. A fraction of the angular momentum is transferred to the accretor and used to spin it up, Fig. 3, bottom right. Even after 41 orbits there is no sign of a merger, instead the separation increases continuously and the mass transfer decreases for almost 20 full orbits (Fig. 3, center). Such a system could possibly evolve into a AM CVn system.

### 4. Conclusions

We have demonstrated the sensitivity to the initial conditions used in double degenerate binary simulations and have put particular emphasis on the accuracy of our starting configurations.



**Figure 3.** Evolution of the orbital separation (left), the mass ratio (center) and the spin angular momentum for both the accretor and the donor (right) for a system with  $q = 0.5$  (upper panels) and  $q = 0.27$  (lower panels).

Contrary to earlier SPH simulations our binaries are *not* disrupted after a few orbital periods, but instead transfer mass for dozens of orbits. In as far as we can compare it, our simulations are in perfect agreement with the recent simulations of D’Souza et al. (2006).

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